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14. ABSTRACT

The aim of this project was to study mixing forced by tidal flow over sudden changes in topographic slope such as near the shelf-break, using high-resolution nonhydrostatic numerical simulations employing the MITgcm. Two different sets of simulations have been performed, the first a parameter survey involving 4 different topographies and a wide range of forcing amplitudes; the second a set of simulations of flow over the Hawaiian ridge. The most exciting scientific result is the importance of internal hydraulic jumps in generating tidal mixing at large amplitude, steep topography. An additional important result is the quantification of the relative amount of energy dissipated locally compared to that radiated away as internal tides – whereas this fraction is only 10% for most topographies, it increases greatly for very narrow topography.

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Tidal Mixing at the Shelf Break

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LONG-TERM GOALS

Our long-term goal is to understand mixing processes near topography, especially those resulting from the tidal flow, and to quantify and parameterize this mixing in global and coastal numerical prediction models. This study focuses on one aspect of tidal mixing: that close to the shelf break.

OBJECTIVES

This project aims to understand mixing processes initiated near the shelf break by the motion of the tides over the shelf break topography, with a focus on the mixing off-shore of the shelf-break.

Specific questions to be examined include:

a) How much energy is converted from the barotropic tidal flow into baroclinic motion, and how much of the baroclinic energy is dissipated and/or used for mixing near the shelf-break, as compared with the fraction of energy radiated away as internal tides?

b) What factors of the topography, stratification and flow determine the width of the internal tide beam generated at the shelf-break?

c) Under what conditions, particularly of topographic slope and curvature, is an internal hydraulic jump created offshore of the shelf-break?

d) When there is transient hydraulic control at the shelf-break, where does the mixing occur - primarily as overturning in an internal hydraulic jump, or as shear instability?

e) How are the flow and mixing modified by changes in stratification and three-dimensional topographic features?

APPROACH

Using the nonhydrostatic MIT ocean model configured for small domains with continental shelf-break topography, 2 and 3-dimensional numerical simulations are performed. Topography and stratification are imposed to match that of regions of recent observations of tidally driven mixing near the shelf-break, e.g. Monterey Canyon and Hawaii. Barotropic tides are forced through a sinusoidal body force, with tidal ellipses prescribed from observations.

WORK COMPLETED

A total of 20 2-dimensional simulations have been carried out, in order to explore parameter space. The simulations have focused on varying the topography (different height and steepness of the topography) and the amplitude of the barotropic forcing. Analysis has focused on diagnosing the rate of conversion of energy from barotropic to baroclinic modes, the dissipation near the topography, and the appearance of internal hydraulic jumps. These simulations have been for idealized isolated-ridge type topographies. This work was included in an invited talk presented at the Symposium on Ocean Mixing in Victoria in October 2004. A manuscript describing this work, "Preliminary simulations of internal waves and mixing generated by finite amplitude tidal flow over isolated topography" is in press in Deep Sea Research. In collaboration with members of the Hawaiian Ocean Mixing Experiment Team, specifically Jody Klymak, simulations of tidal flow over the Hawaiian ridge have been carried out, initializing the model with observed stratification and topography, and forcing it with observed tidal flow. Legg moved to Princeton University in September 2004, and has continued to receive funding through a subcontract to Princeton University.

RESULTS

(a) Conversion of energy from barotropic to baroclinic tide, dissipation of energy.

For low amplitude gentle topography, the tidal energy conversion is found to very closely match the prediction of Bell (1975), extended by Khatiwala (2003) for finite depth fluid. For both steeper topography, and tall topography occupying a significant fraction of the total ocean depth, higher conversion rates are found, as predicted by St Laurent et al (2003). As the amplitude of the forcing increases, the conversion rate predominantly scales like the barotropic velocity amplitude squared, although some steep topographies show small deviations from this overall scaling. The dissipation rate is around 10% of the conversion rate for most of the topographies examined, but the narrowest topography examined shows a much higher dissipation rate. The predominant factor influencing the dissipation appears to the length-scales of the internal waves generated, which in turn is determined by the length-scale of the topographic feature. Figure 1 shows the conversion rate, the dissipation rate, and the ratio between dissipation and conversion for the 20 different Gaussian topography simulations.

(b) The width of the internal tide beam

In the simulations completed for this project, a beam-like structure is seen for all steep topographies, i.e. where the slope is steeper than the wave characteristic. However, even when an internal tide beam is visible, much of the energy is still contained within low vertical modes for topography with large horizontal scales. The predominant influence on the horizontal and vertical scale of the energy containing modes is the horizontal scale of the topography, with narrow topography leading to high vertical modes. Figure 2 shows the baroclinic velocity field for 4 different topographies with identical forcing and topography.

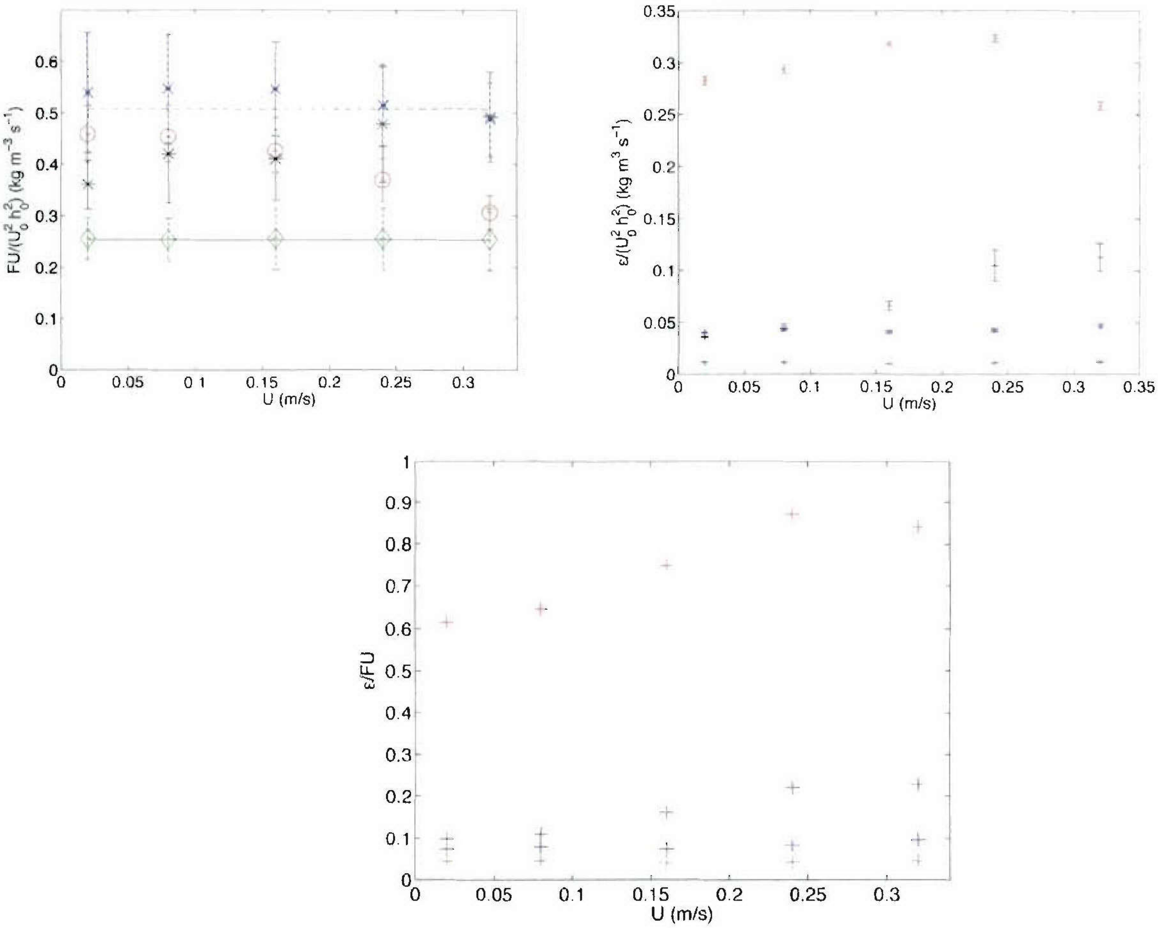

Figure 1: Energy conversion from barotopic to baroclinic motion for 4 different topographies at 5 different tidal forcing amplitudes. Top left: Energy conversion rate. Top right: Dissipation. Bottom: Ratio of dissipation to energy conversion rate, all shown plotted against the barotropic tidal velocity amplitude U. In all three panels the different topographies are Gaussian ridges with a height h and a half-width L, with values: (i) h=200m, L=10000m (green); low,wide topography; (ii) h=200m, L=413m (red); low, narrow topography; (iii) h=2350m, L=4857m (blue); tall, wide topography; (iv) h=2350m, L=1215m (black); tall, narrow topography. In all cases the total depth of the fluid is H = 4700m, stratification is uniform with buoyancy frequency N = 8 x 10^{-4} s^{-1} and the forcing is at the M2 tidal frequency ω = 1.41 x 10^{-4} s^{-1}. The energy conversion (top left) shows that the steeper topographies all have higher conversion rates than the low,wide topography (green) which has a conversion rate which matches that predicted by Bell (1975) (solid line). The dashed line shows St Laurent et al's (2003) prediction for the conversion rate for a knife-edge ridge in infinitely deep fluid and the dotted line shows their prediction for the conversion rate for a knife-edge ridge with topography extending half the depth of the fluid. The dissipation (top right) shows that the low,narrow topography has the largest dissipation rate (when scaled by the height of the topography) and the bottom figure shows that the ratio between dissipation and energy conversion is about 10% for most calculations, except for the low, narrow topography where it is considerably greater.

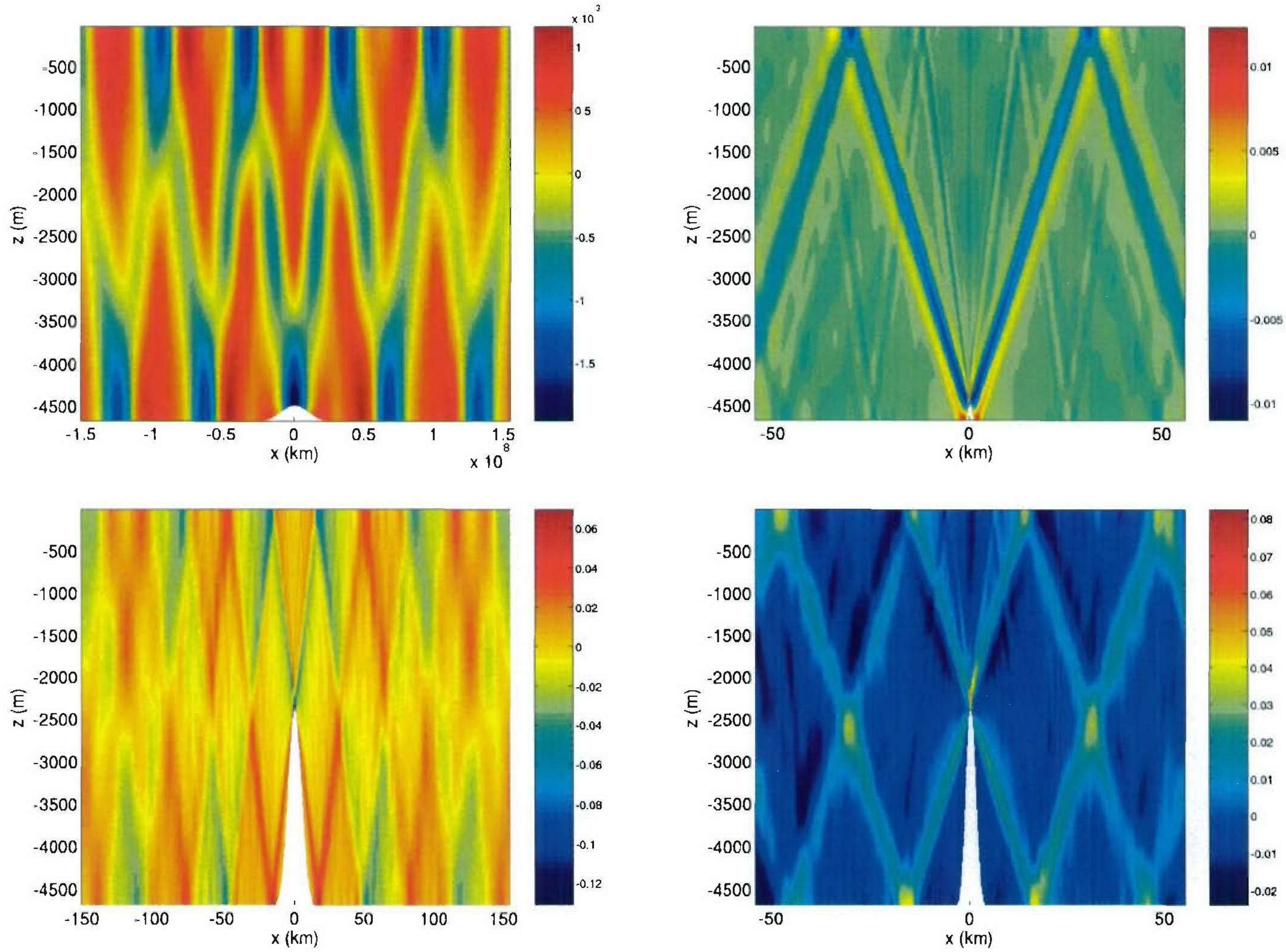

Figure 2: Snapshots of the baroclinic velocity field for 4 different topographies. In all 4 cases, the barotropic tidal velocity amplitude is 2 cm/s. Other details are as given in the caption to Figure 1. Top left: low,wide topography, h=200m, L=10000m; top right: low, narrow topography, h=200m, L=413m; bottom left: tall, wide topography, h=2350m, L=4857m; bottom right: tall, narrow topography, h=2350m, L=1215m. Note that color scales and horizontal scales are different in all 4 images, due to the different sizes of the topography. For low,wide topography (top left) a mode 1 internal tide is seen, while for low,narrow topography a narrow beam is seen. The tall wide topography and tall, narrow topography, both of which are wider than the low,narrow topography have some mode 1 character and some beam-like character in their response.

(c) Internal hydraulic jumps

Internal hydraulic jump-like features are seen only for large-amplitude steep topography and large-amplitude barotropic tidal forcing. A possible criteria for the appearance of internal hydraulic jumps may be Froude number = $U/(Nh) < 1$, and tidal excursion parameter $U/(\omega L) > 1$, where U is the amplitude of the barotropic tidal forcing in deep water, N is the buoyancy frequency, h is the height of the topography, ω is the frequency of the tidal forcing and L is the horizontal lengthscale of the

topography. When internal hydraulic jumps appear, they are responsible for localized mixing at the topography. Figure 3 shows the isopycnal displacement for 4 different topographies; only the largest amplitude topographies show possible internal hydraulic jumps.

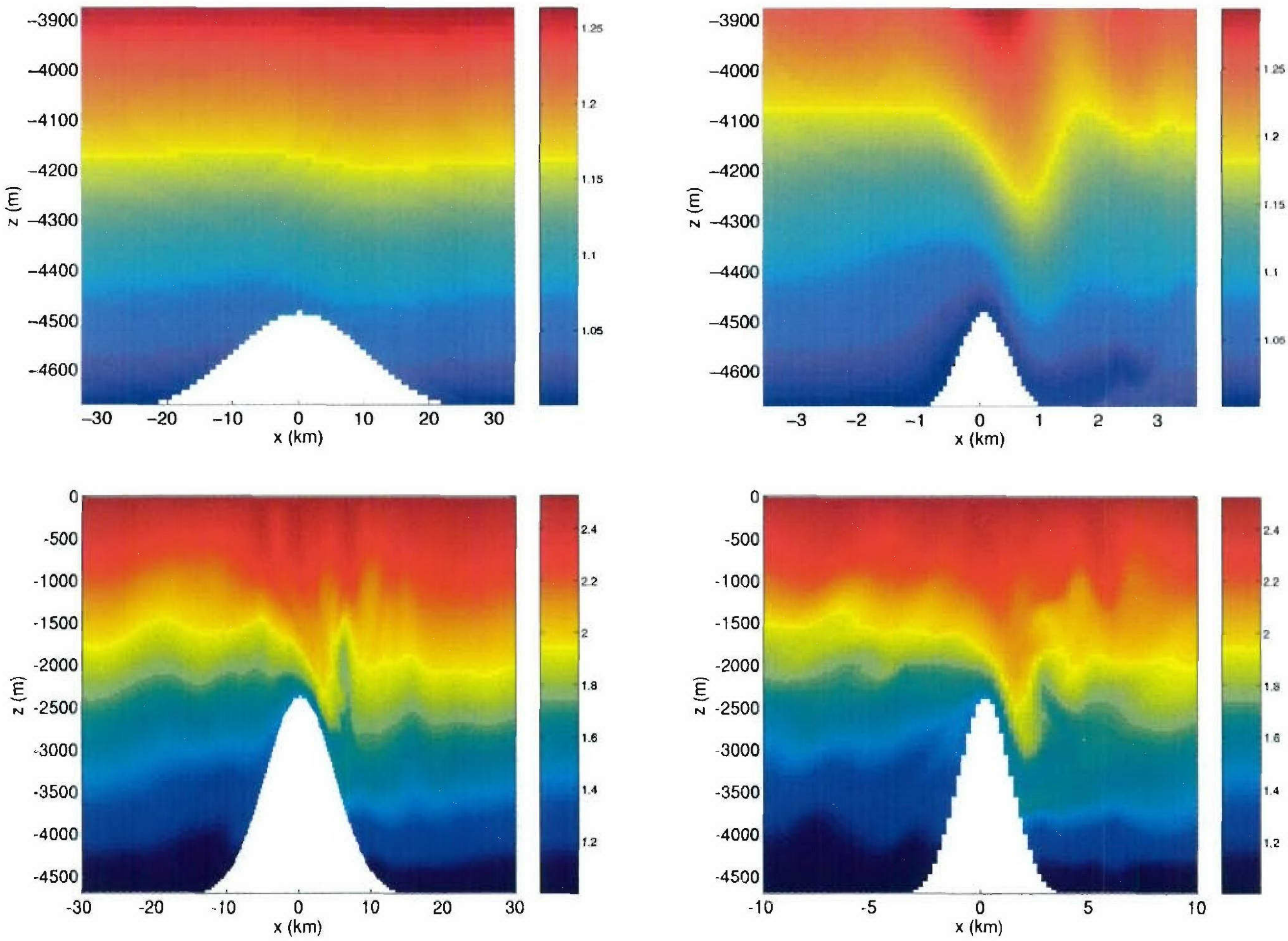

Figure 3. Snapshots of the temperature field for 4 different topographies for barotropic forcing velocities of U=24cm/s. The topographies are as described in the previous figure caption. Top left: low, wide; top right: low, narrow; bottom left: tall, wide; bottom right: tall, narrow. For the tall topographies the flow over the ridge causes the isotherms to plunge downward downstream (to the right) of the ridge followed by a rebound similar to an internal hydraulic jump, with some associated overturning.

(d) Internal hydraulic jumps and bores at the Hawaiian Ridge

Two-dimensional high resolution simulations of tidal flow over the Kaena ridge portion of the Hawaiian ridge reveal internal hydraulic jumps occurring every tidal cycle during maximum flow off the ridge, just below the shelf break (see figure 4). Notably the slope is supercritical in this region. As the flow relaxes the internal jump modifies into an internal bore which propagates up the slope and onto the plateau, associated with significant overturning as it moves. The amplitude of the internal hydraulic jump and hence the associated mixing are strongly dependent on the tidal forcing amplitude.

These simulations are proving very useful in interpreting observations from the Hawaiian Ocean Mixing Experiment, in particular the source of mixing observed at flow reversal. Similar internal hydraulic jumps are seen on both flanks of the ridge, but are most marked at the steeper flank, which has more sudden changes in slope near the shelf break. Simulations are continuing to elucidate the role that the steepness and curvature of the slope below the shelf break play in controlling the appearance of internal hydraulic jumps. We expect these results to form part of a publication in collaboration with the HOME observationalists.

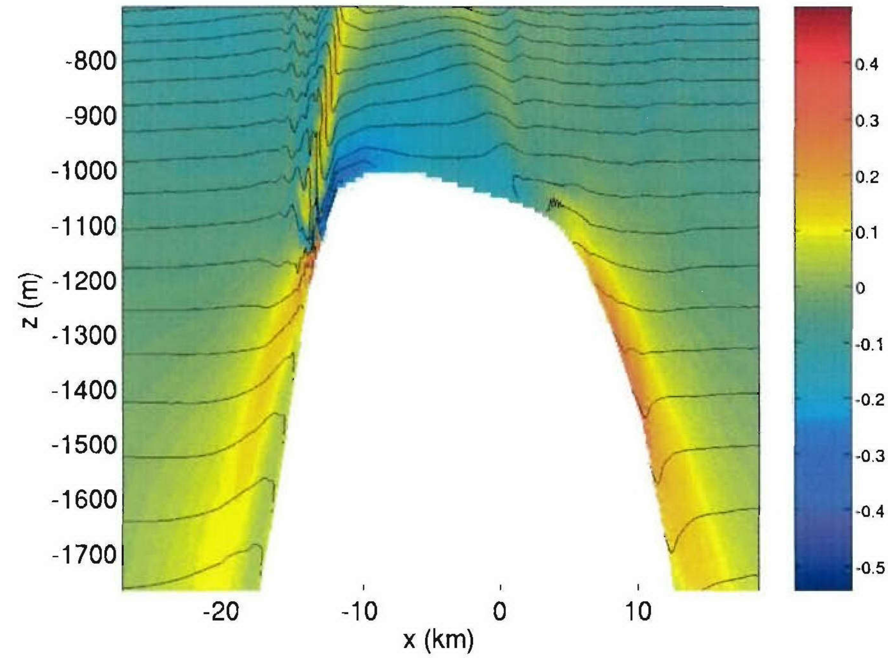

Figure 4. A snapshot of flow velocity (in color) with isopycnals overlain from a simulation of tidal flow over Kaena Ridge, Hawaii, shown at the time of barotropic flow reversal. The simulation is forced with an M2 tide of amplitude 5cm/s, corresponding to the observed spring tide amplitude. Just below the leftmost shelf-break an internal bore is seen, associated with strong convergence, and overturning isopycnals. This bore propagates up the slope and onto the plateau, causing near boundary mixing as it goes. Only a small portion of the total numerical domain is shown, from a depth of -700m to -1700m, to focus on the top of the ridge.

IMPACT FOR SCIENCE

The information provided by these simulations will be useful for parameterization of tidal mixing in coastal, regional and global ocean models. For example global tidal mixing parameterizations need to determine how much tidal energy is used for local mixing and how much is radiated away as waves – these results can reduce the uncertainty in this estimate. For studies of nonlinear internal waves on the coastal shelf, an understanding of generation mechanisms is important – the internal bores resulting from the internal hydraulic jumps at the shelfbreak are one possible mechanism.

RELATED PROJECTS

This work draws on observational data collected as part of previous (e.g. LIWI) and ongoing (e.g. HOME) field programs. The processes by which internal bores are generated and propagate onto the shelf connect with the Nonlinear Internal Waves Initiative (NLIWI).

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